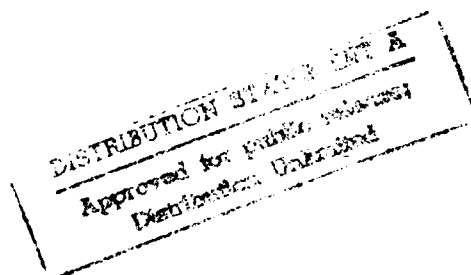AD-A271 740

US Army Corps of Engineers
Water Resources Support Center
Institute for Water Resources

FIRST STEPS IN THE DEVELOPMENT OF A METHOD FOR EVALUATING ENVIRONMENTAL RESTORATION PROJECTS

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Russell, Clifford S., Victoria Klein and Jennifer Homan
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Throughout the nation, there is an increased awareness of, and concern for, environmental restoration. Within the U.S. Army Corps of Engineers, new authorities are providing more and more opportunities to pursue environmentally oriented projects. This increased emphasis on the environment, however, brings a concomitant need for improved techniques for valuating and comparing environmental projects and programs. There is almost always more than one way to address a specific objective, and typically more projects and programs waiting to be pursued than funds available. The purpose of this study is to provide conceptual underpinning and preliminary guidance on the development of an evaluation framework and measurement techniques that will contribute to a practical partnership between ecology and economics. The work reviews, evaluates and draws conclusions about research needs from the published and unpublished literatures bearing on the relation between ecological systems and economic notions of effectiveness and evaluation.

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FIRST STEPS IN THE DEVELOPMENT OF A METHOD FOR EVALUATING ENVIRONMENTAL RESTORATION PROJECTS

A White Paper

by

Clifford S. Russell

With the collaboration of

Victoria Klein
Jennifer Homan

Planning and Management Consultants, Ltd.
P.O. Box 1316
Carbondale, IL 62903

for

U.S. Army Corps of Engineers
Water Resources Support Center
Institute for Water Resources
Fort Belvoir, VA 22060-5586

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PREFACE

This report was prepared as part of the U.S. Army Corps of Engineers (COE) Evaluation and Formulation of Environmental Projects Work Unit, within the Planning Methodologies Research Program. Mr. William Hansen and Mr. Darrell Nolton of the COE Water Resources Support Center (WRSC), Institute for Water Resources (IWR), manage this Work Unit under the general supervision of Mr. Michael Krouse, Chief, Technical Analysis and Research Division; Mr. Kyle Schilling, Director, IWR; and Mr. Kenneth Murdock, Director, WRSC. Mr. Robert Daniel, Chief of the Economic and Social Analysis Branch (CECW-PD) and Mr. Brad Fowler, Economist (CECW-PD) served as Technical Monitors for Headquarters, COE.

The work was performed by Planning and Management Consultants, Ltd. (PMCL), under Task Order 0029, Contract No. DACW72-89-D-0020, in collaboration with Dr. Clifford S. Russell, Ms. Victoria Klein, and Ms. Jennifer Homan, all of the Vanderbilt Institute for Public Policy Studies, Vanderbilt University. Dr. Russell was the principal investigator and primary author.

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I. INTRODUCTION

In a world of persistent federal budget deficits tied to politically sacred entitlement programs, every proposal for discretionary spending is bound to be subject to intense scrutiny. In an organization such as the U.S. Army Corps of Engineers which has a decentralized structure and in which initiatives are generated in the field, responding to the resulting pressures for budget justification can never be easy. Even within the Corps, however, some problems are tougher than others. If the linkage between proposed spending and anticipated benefit is weak, for example, skeptics or just plain penny pinchers will find it easier to reject the project. If the anticipated benefit is naturally measured in dollar terms, using market prices as the basis for those terms, the "sell" before OMB or Congress will usually be easier than if the benefit appears to be purely aesthetic or to involve, for example, preservation of a cultural or historical site with only narrow appeal to potential visitors or voters. Thus, it is generally going to be easier to explain and justify choices among predictive maintenance projects at existing Corps hydroelectric facilities than those among possible environmental restoration or mitigation projects. Nonetheless, choices among restoration projects do have to be made and justified, both to local sponsors and to national political powers. Improving the methods by which these choices are made is the ultimate goal toward which this white paper is directed.

Because the choices among alternative restoration projects must be made in a decentralized budget-building process, the demands of any choice-informing process must be kept modest in terms of money, time, and the need for expertise in the field. This is the requirement for practicality. At the same time, any method employed must be conceptually defensible in both its environmental or ecological and economic dimensions. Finally, any method, if it is to be useful to the Corps, must lend itself to reproducibility at higher command levels and must produce outputs comparable across the entire set of projects—at the district, districts at the division, and divisions at headquarters.

Clearly there is the potential for conflict among these requirements, especially between practicality and defensibility. Moreover, there is the potential for tension between the needs of local and of national decision processes. Not only do local representatives think of benefits differently than do national agency executives, a fact long recognized in *Principles and Guidelines*, but national agency flexibility also may be reduced by requirements such as certain ecological systems or certain plant or animal species be considered of higher priority than others. In addition, the information that could smooth a local negotiation with potential sponsors might be difficult to fit within the requirement for reproducibility up the chain of decision and command.

All these problems exist in other agencies and problem contexts, of course. But they are made even more significant in environmental restoration decisions by underlying tensions between the disciplines of ecology and economics—notwithstanding their shared root in the Greek *eco* "house or household" to which environmental commentators are fond of pointing. These tensions reveal themselves in many ways, but most often and obviously they take the form of objection by ecologists to the use of "the measuring rod of money"—the ultimate tool of the

1

economist. Sometimes this objection reflects a simple misunderstanding of economics, as in the assertion that goods and services that do not trade in markets are systematically undervalued by economists. Other contributors to this general debate, such as Kelman (1981), are more sophisticated and rely for the force of their arguments on ethically based propositions, e.g., that by the very act of pricing goods and services that should be without price we cheapen them and harm our deeper cultural values as well.

This white paper will not resolve the debate between the hard cores of the two disciplines. Rather, the view taken here is that practical progress—for both the Corps and the larger society—can be made by looking to those who are willing to work across the boundary. Collaborating on the development of practical methods will help to cool the rhetoric while it helps to solve the decision problem. It is important, however, to realize that this sort of collaboration is difficult because of the rhetoric layered on the more common problems of unshared jargons and different mathematical techniques. If the Corps is to succeed on its own terms and make a broader contribution, it will be necessary for each research project and case study along the way to be interdisciplinary. Letting each discipline go its own way and trusting to a subsequent effort at synthesis is a recipe for disaster. Further, this means that patience and longer-than-usual project lives will be necessary. Despite the existence of a field called ecological economics, complete with its own international society and journal, there are few individuals currently equipped to bridge the traditional gap. Even those who are predisposed to do so will need some learning time.

The remainder of this paper is divided into five sections. In the next section, several important conceptual issues are discussed as background for the remainder of the enterprise. This conceptual discussion was developed in part, from the annotated bibliography compiled concurrently for the present research exercise (Klein et al. 1992). The three following sections deal with short-, intermediate-, and long-run problems and research strategies. That is, for each run, comments on assisting decision making are set out, though these necessarily became more speculative as time from the present lengthens. In addition, research opportunities are identified, with an overall goal of breaking out of current limitations. The final section offers some concluding remarks and a summarization of an appropriate research program.

II. CONCEPTUAL ISSUES

A. NOTES ON CURRENT PRACTICE, EXTENSIONS, AND DIFFICULTIES

Current Corps practice in the analysis of environmental restoration and mitigation alternatives is habitat based, although, as discussed below, other considerations usually are involved and may, in fact, dominate the habitat analysis results. As discussed in the Greeley-Polhemus Group (1991) report, the dominant methods for the habitat part of project analysis are the Habitat Evaluation Procedure (HEP), the Pennsylvania Modified version of that procedure (PAM HEP), and the Habitat Evaluation System (HES). All three aim at creating scalar summaries of project outputs by weighting the number of acres of land or water involved by an index number that attempts to capture the suitability of those acres as wildlife habitat, both game and nongame.[1] More recent work, directed specifically at the bottomland hardwood forest systems of the southeastern U.S., attempts to take an ecological community view, but also aims at an index number weight for acreage (O'Neil et al. 1991).

For both restoration and mitigation projects, the methods involve comparing with- and without-project conditions in terms of the weighted habitat acres and other output indicators. Mitigation projects are seen as parts of larger construction projects, so care must be taken in specifying what the terms "with project" and "without project" mean in any particular application. Other difficulties along this line are discussed below. Possibilities that may be relevant in achieving mitigation include changing the larger project design or operating rules, managing project land or water to suitably enhance their habitat, and "compensating for impacts by replacement or substitution of resources"[2] (Greeley-Polhemus 1991, p. 3). For restoration of some historically harmed area, both the management and replacement/substitution alternatives are, at least on the surface, possible categories of action.

The costs of any mitigation or restoration alternative can, in principle, usually be calculated using reasonably straightforward methods. However, a mitigation alternative that interferes physically with overall project design or operation may create some costing difficulties because costs will show up as project benefits foregone, not as simple capital and operating costs for facilities or ongoing costs of management policy implementation. For a very interesting example of analysis involving foregoing project outputs, see Kneese et al. (1988).

To better understand how complicated the analysis of a large-scale restoration project can become, especially where more than one public agency and thus more than one agenda are involved, consider some of the information gathered and displayed in the decision documents for

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[1]For an example of application of HEP, albeit a necessarily ad hoc one, see the Flood Storage Alternatives Study for the Santa Ana River, done by the Los Angeles District in 1985. (U.S. Army Corps of Engineers 1985).

[2]The concepts of replacement and substitution are in themselves worth some discussion and receive such below.
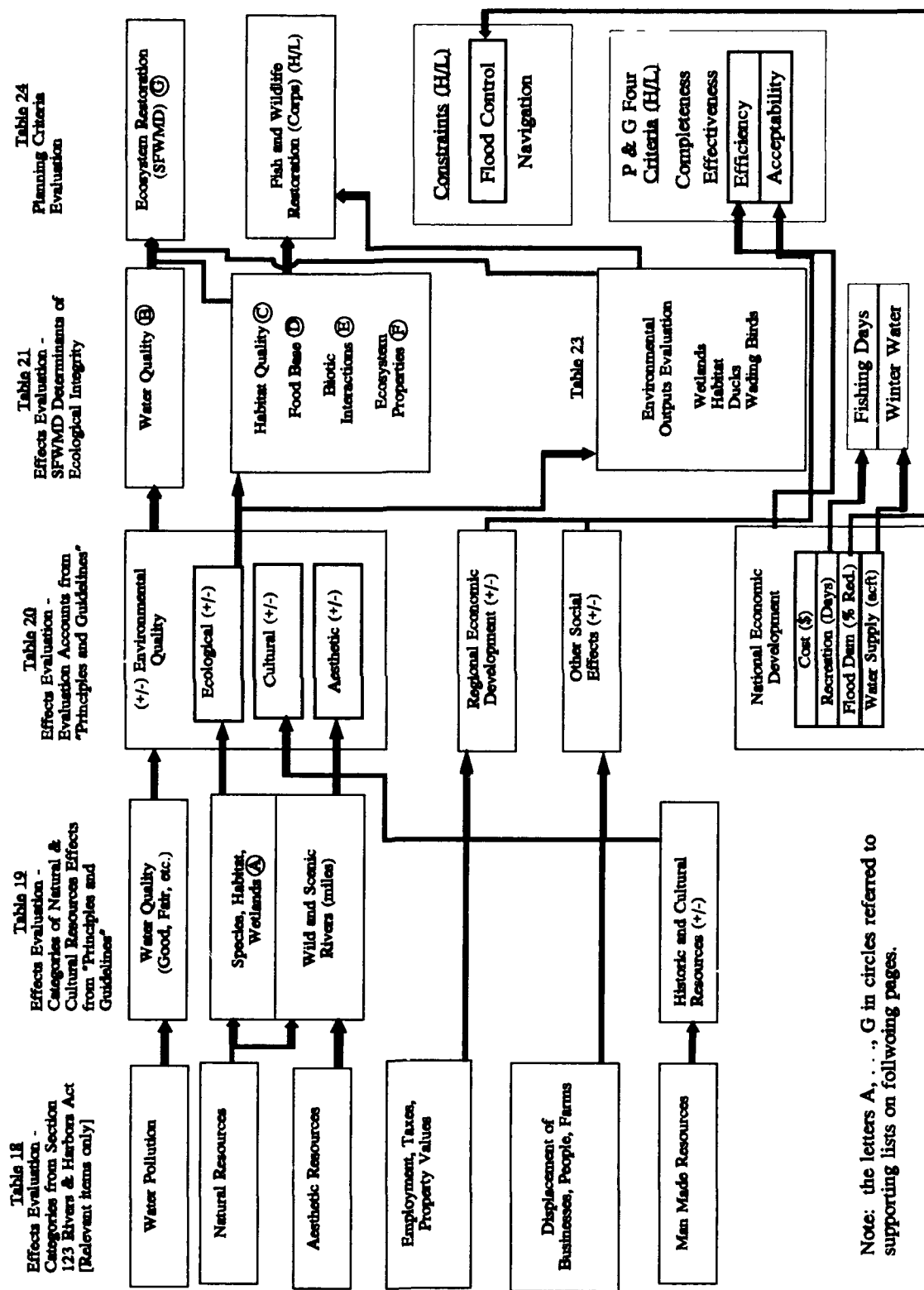
the Kissimee River, Florida restoration project.[3] Figure II.1 provides a schematic of the effects considered and the overlapping of a variety of requirements, guidelines, and a priori criteria. Supplementai information for Figure II.1 is found in Table II.1. Several observations are worth making on the basis of this figure and its supporting lists:

- While there are many effects and criteria listed on the "planning criteria evaluation" of "Table 24," the Corps emphasizes fish and wildlife restoration, considers as constraints requirements involving flood control and navigation, and intends ultimately to address the four criteria from *Principles and Guidelines*: completeness, effectiveness, efficiency, and acceptability.

- Within each stage of inquiry as defined by the concerns of different laws, agencies, and by *Principles and Guidelines*, the individual effects are predicted and stated in different ways and units, ranging from milligrams per liter to acre-days, to numbers of individual ducks and wading birds. Many of the effects are evaluated only as plus or minus—that is, whether the project and its alternatives are predicted to improve or lead to deterioration of the current situation.[4] It is no criticism of the Corps' methods, or those of SFWMD, to point out that no tool exists for combining all this information other than through the judgments of those preparing and critiquing the report.

- Thus, the claim made in the feasibility report (Corps of Engineers 1991, page 4 of the "Syllabus") that the preferred alternative is the most cost effective of those analyzed, stretches the meaning of that phrase well beyond its breaking point. It might be that a vote would show this project to be preferred by a majority of area residents, by national environmentalists, by members of the Florida congressional delegation or by any and all other constituencies except local farmers and boaters. But there is no way to tell whether it is cost effective because effectiveness here is a multidimensional notion involving everything from changes in dissolved oxygen to frequency and duration of flooding of the Kissimee Floodplain.

- Thus, there is no straightforward way to convey to individuals or groups outside the planning group the basis for the decision reached unless it dominates all alternatives in all or nearly all dimensions. The only answer to a challenge by an OMB examiner must effectively be, "This is our professional judgment."

- When it comes to deciding how to spend a limited restoration/mitigation budget in the face of a set of competing projects analogous to the Kissimee example, there emerges

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[3]The question for the Corps here was whether or not to participate in a restoration project designed and advocated by the South Florida Water Management District (SFWMD). The project is aimed at undoing the damages created by canalizing the river in the 1950s. (See Corps of Engineers 1991.)

[4]It is worth pointing out that the details in the tables used to construct Figure II.1 are supported by yet more micro analyses of specific areas, species, and situations.

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Figure II-1. A Schematic of the Kissimee Project Evaluation Method

Table 18
Effects Evaluation -
Categories from Section
123 Rivers & Harbors Act
[Relevant items only]

Table 19
Effects Evaluation -
Categories of Natural &
Cultural Resources Effects
from "Principles and
Guidelines"

Table 20
Effects Evaluation -
Evaluation Accounts from
"Principles and Guidelines"

Table 21
Effects Evaluation -
SFWMD Determinants of
Ecological Integrity

Table 24
Planning Criteria
Evaluation

Water Pollution

Natural Resources

Aesthetic Resources

Employment, Taxes, Property Values

Displacement of Businesses, People, Farms

Man Made Resources

Water Quality (Good, Fair, etc.)

Species, Habitat, Wetlands Ⓐ

Wild and Scenic Rivers (miles)

Historic and Cultural Resources (+/-)

(+/-) Environmental Quality

Ecological (+/-)

Cultural (+/-)

Aesthetic (+/-)

Regional Economic Development (+/-)

Other Social Effects (+/-)

National Economic Development

Cost ($)
Recreation (Days)
Flood Dam (% Red.)
Water Supply (acft)

Water Quality Ⓑ

Habitat Quality Ⓒ
Food Base Ⓓ
Biotic Interactions Ⓔ
Ecosystem Properties Ⓕ

Table 23
Environmental Outputs Evaluation
Wetlands
Habitat
Ducks
Wading Birds

Fishing Days
Winter Water

Ecosystem Restoration (SFWMD) Ⓖ

Fish and Wildlife Restoration (Corps) (H/L)

Constraints (H/L)
Flood Control
Navigation

P & G Four Criteria (H/L)
Completeness
Effectiveness
Efficiency
Acceptability

Note: the letters A, ..., G in circles referred to
supporting lists on follwoing pages.

TABLE II.1

A SCHEMATIC OF THE KISSIMEE PROJECT EVALUATION METHOD

List A: Species, Habitat, Wetlands Effects
          Endangered or threatened species (species list)
          Fish and wildlife habitat (habitat units -- weighted acres)
          Wetlands (acres)

List B: Water Quality Indicators
          Dissolved Oxygen (mg/l)
          Nutrients (mg/l)
          Turbidity (low/high)

List C: Habitat Quality Indicators
          Wetlands (acres and by extent of "mosaic")
          Overland floodplain flow (description)
          Winter water (description)
          Refuge availability (acres)
          Riverine habitat diversity (high/low)
          Substrate (good/poor)
          Flow velocity relative to species needs (good/poor)

List D: Food (Energy) Base Indicators
          River to floodplain contributions (description)
          Riparian vegetation to river contributions (description)
          Floodplain to river contributions (description)
          Instream primary production (description)

List E: Biotic Interactions Indicators
          Species diversity (high/low)
          Trophic structure (complex/simple)

List F: Ecosystem Properties Indicators
          Resilience (high/low)
          Biological dynamics (description)

List G: Ecosystem Restoration Criteria
          Discharge characteristics (high/low)
          Flow velocities (high/low)
          Overbank flow (high/low)
          Stage recession rates (high/low)
          Floodplain inundation frequencies (high/low)

an even more difficult problem: The "natural" dimensions on which the several competing projects are subjectively judged will in general be different from project to project. Thus, while aquatic items dominate the Kissimee analysis, terrestrial items appear to dominate the Santa Ana mitigation study mentioned in footnote one.

Thus, it seems fair to say that two linked shortcomings need to be addressed in the long run if restoration and mitigation projects are to receive comparable and persuasive evaluations. First, while wildlife habitat may in some cases be a satisfactory surrogate for a broader notion of ecological functioning, in general the concern of Corps planners will almost certainly have to broaden—toward the kinds of considerations emphasized by the SFWMD effects and criteria as outlined in the right-hand portion of Figure II.1. Second, the difficulties in the way of combining those multiple effects and criteria must be addressed.

Improving the way restoration decisions are informed will not be easy, in part because the technical tools currently lag well behind the sense of what ought to be done and partly because the decision process itself is fragmented and complicated, so that information useful at one level may not be useful at another. The complications here include the importance of local goals in the design of a project local sponsors can support on one extreme, and national priorities and requirements that must influence national choices among competing projects at the other.

B. EXPANDING ON HABITAT IN CONSIDERING ECOLOGICAL SYSTEMS

Criticisms of reliance on wildlife habitat as an indicator of ecological system function may be seen as arising from two sources: one ethical and the other practical. First, ecologists and environmental ethicists would claim that it is our obligation to try to understand environmental systems in their own terms and not by imposing our own output desires on them. In starkest terms, just because we like to fish for trout and bass and hunt for deer and turkeys is no reason to judge which of two possible states of an area is to be preferred on the basis of trout, bass, deer, or turkey production. The community models cannot be put down this easily, of course, for they contain no simple choice based on human activities. However, even one of these more inclusive and complex approaches can be criticized for failing to do justice to the multiple functions of ecological systems. That is, practically speaking, habitat measures may be poor indicators because of competition among the many functions ecological systems perform that benefit humans in the long run.

Consider, for example, the following list of nonhabitat ecosystem functions (e.g., Nash 1991):

> Some Nonhabitat Functions of Natural Systems:
> Flood absorption
> Nutrient (and even toxics) sequestration
> Landscape variety provision
> Erosion prevention
> Aquifer recharge
> Carbon fixation (atmospheric CO_2 stripping)

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Each of these is potentially competitive with the provision of habitat, more certainly the more narrowly the species or community of interest is defined. That is, for example, if a method for characterizing the "output" an ecological system has, as one dimension of judgment, the success of one species or group of species that thrives on dry ground, there will be a clear conflict between the habitat and flood absorption functions. Similarly, the generally acknowledged need for large areas to remain undisturbed and intact in order to maintain populations of certain native species is, in general, competitive with the provision of landscape variety. Analogously, there are conflicts possible among the nonhabitat functions in even this short list.[5]

It would be wrong to give the impression that the definition of "function" was a settled matter or that there is agreement on what constitutes an acceptable catalog of functions for any given system type. Indeed, it seems that function is sometimes taken to mean service or subsidy to humanity, sometimes service to the rest of the system and sometimes descriptive characteristic.[6] The notion and relevant terminology must be cleared up before they can be routinely useful. For purposes of this paper, however, all that is needed is a preliminary understanding of what function means and why habitat cannot act as a proxy for all possible functions; that is, some understanding of the possibilities for competition among functions is required.[7]

However, if the challenge of looking at multiple functions is accepted, we confront the second difficulty mentioned above—how to combine information, or predictions, about multiple outputs from a restoration or mitigation project so as to allow for persuasive and reproducible statements about preferences among competing projects, that is, how the cost-effectiveness problem is to be solved.

As a final observation, note that even if the cost-effectiveness problem is solved—a persuasive scalar measure of ecological system output is manufactured—there remains the question of how to choose the effectiveness target. In general, there are two solutions. One is technical and analogous to, but more demanding than, cost-effectiveness analysis; the other messy and political but realistic in the best sense of the word. The technical solution is cost-benefit analysis, in which the outputs of the ecological prediction techniques are valued by some method to put them in dollar terms for comparison with costs. The political solution depends on the

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[5]There may also be complementarities that also make output measurement more difficult. For example, Walker (1991) discusses the link between biodiversity (species richness) and ecosystem functioning more broadly.

[6]Sometimes discussions at the meetings of the Ecosystem Valuation Forum, sponsored by EPA and organized by the Conservation Foundation with the idea of forging a way of thinking about overall ecosystem value in policy contexts, bogged down on these terminological matters. One particular problem that came up several times was whether it is useful to think of ecosystem support as an ecosystem function that should be taken into account. The view adopted in this paper is that ecosystem support is analogous to an intermediate good in economics. Its value shows up in the final functions provided by the system in question.

[7]One practical effort to deal with functions as the basis for judgment does exist. The Wetlands Evaluation Technique (WET) is "designed to give a broad overview of functions of wetland habitat" (Greeley-Polhemus Group 1991, p. 28; Adamus et al. 1991).

observation that, in most environmental policy areas, the political process sets the goals and executive agencies work to meet them in cost-effective ways—to the extent that those ways have not themselves been politically proscribed (see Section E).

C. PREDICTING THE ECOLOGICAL CONSEQUENCES OF RESTORATION AND MITIGATION ACTIVITIES

While it was neither planned nor possible to do a thorough state-of-the-art assessment of the predictive capabilities of ecological science in relation to the Corps' interest in restoration and mitigation activities, enough has been learned to support some overall conclusions. To anticipate the conclusion, understand at the outset that going beyond the common habitat models is not going to be easy.[8] Ecology is at least as primitive as economics in its ability to model the macro systems in which it is interested. Nevertheless, let us look briefly at four general types of ecological models for an idea of alternative approaches.

1. Habitat Models

The Corps is already familiar with habitat-based models, in which accumulated information about one or many wildlife species is combined in somewhat formal ways to create indexes of habitat suitability. A quite sophisticated effort, already referred to, is described in the "Biological Report" of O'Neil et al. (1991). The authors have searched the literature on species that use bottomland hardwood forests of the southeastern U.S., and have produced a set of eight sample plot and five tract-level measures, which in turn are transformed into index numbers via linear and nonlinear transformations that compress everything into the 0, 1 interval. Their model's key features are the chosen measurements and the transformations, the latter attempting to capture what happens to general, not species specific, habitat suitability as a particular measure (e.g., number of ground-level features present on a plot, such as live vegetation, leaf litter, stumps, logs, and holes) increases.

This work makes another important point that will be relevant as well to a preliminary assessment of other models: space, particularly the size of the tract of habitat being evaluated, is important in itself. At least in terrestrial systems, it is not sufficient to look at point models of processes and then inflate the results linearly to the site size in question. What can happen in any randomly chosen square meter of the site is a function of the site's total size—a function which probably is nonlinear.

The problems with this habitat-model effort and its earlier, perhaps more familiar, cousins include the following:

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[8]This is not to say that there are no predictive ecological models out there. There are scores, perhaps hundreds, for just about every sort of ecological system, from tundra to rocky northern ocean shores, from desert to southern ocean salt marsh. They also come in many forms.

- The ways in which the insights from available literature are combined and quantified are entirely ad hoc. This goes for what is measured, how the measurements are transformed into 0, 1 variables, and how those variables are combined into an overall index number (see Appendix A).

- Though predictions are implicit in the resulting index numbers and habitat units, they are not stated—and indeed cannot be stated—in ways that are straightforwardly verifiable.[9]

2. Species Population Models

Species population models seem to be most prominent in the fisheries field where they are used regularly in the setting of harvest quotas. They are based on the fundamental relations of population dynamics and can include many key human interventions in a straightforward way, harvest most importantly. There often is very little or no ecological detail specified outside the population dynamics relations, though the role of the larger system in limiting growth rates or ultimate population size is implicit in the shapes and locations of those relations. Because of their focus on one or a few species, usually of direct interest to humans, they are cousins of the habitat models and share the fundamental conceptual shortcomings of those in the mitigation/restoration context. They do have the advantage of producing quite explicit predictions that can be straight-forwardly verified where spatial scope is limited, as in a small stream, a limited woodland, or a naturally enclosed canyon[10] (See, for example, Fisher et al. 1991).

3. Energy or Carbon Flow Models

Also very widely developed and used, though seemingly more in research than management, are the carbon or energy flow models. They involve the definition of compartments (state variables); specification of their links with each other and with exogenous sources and sinks of carbon, key nutrients and energy, usually the sun; and creation of a set of partial

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[9]The object of the exercise is to rate tracts relative to a hypothetical optimum capable of supporting "the maximum native species richness of birds, mammals, reptiles and amphibians on a regional scale over a long time period." There is also an assumption "that habitats with higher species richness will have higher population levels for many of those species" (O'Neil et al. 1991, p. 4). Thus, it could be argued that relative species numbers are in fact the predictions of the model. A possible verification technique would be to do the model's index number studies and a species search on a large number of tracts and test the relation between Habitat Suitability Index results and species richness. The central problem would be in devising absolutely unbiased sampling methods, so that the probability of discovering a species representative would be equal for each species across all tracts in the experiment.

[10]A colorful simile, used to describe the difficulty of counting a population of fish in a large body of water, is that the task amounts to estimating the Virginia apple crop by towing a bushel basket behind a light plane up and down the Shenandoah Valley.

differential equations that capture how the links are hypothesized to affect the state variables as time passes. The compartments may be either more or less narrowly defined components of the system being modeled—for example, benthic organisms, or particular families of such organisms or even individual species of such organisms, if that is the level of interest. The more narrowly defined the compartments, of course, the more compartments and the larger the model construction and solution chores. The links can include such processes as the capture of solar energy via photosynthesis, grazing, respiration, and death and decay.[11]

These models have been used for a long time in the water pollution context (e.g., Spofford et al. 1976) and seem to be most highly developed for aquatic systems, but they also exist for terrestrial systems (e.g., Wagenet and Gremney 1983; Boesten and Leistra 1983). For schematics of one such model, see Figures II.2a and II.2b. Tables II.2 and II.3 contain respectively the differential equations, and parameter definitions and values that make the schematic operational.

As specified, the models are usually intended to capture biochemical activity essentially at a point in space, which is usually defined as a three dimensional compartment of small size relative to the overall system being modeled. Expanding their coverage to a particular area—estuary, lake, wetland, forest, etc.—means combining the point or compartment models with some form of spatial dynamics. For water bodies, these dynamics are dominated by the movement of water and the resulting advection and related diffusion of organisms and chemicals. In terrestrial models, movement between compartments requires action by the organisms, and these movements may be caused by forces that are only imperfectly understood or at best difficult to model in the deterministic differential equation framework that routes carbon through the system. Perhaps this explains the relative success of this model type in the aquatic environment.

A big question is whether the models are capable of dealing with the stated problem: What occurs at any single point generally depends on the size of the overall system. This relationship is due to subtle and presumably difficult-to-model processes such as territoriality, predation strategies, and prey self-protection strategies. The question of space and ecological processes at the landscape and regional scale is discussed by O'Neill et al. (1992). Their conclusion strongly suggests that much remains to be done.

> The research agenda for landscape studies can be stated simply: How do ecological processes interact with the environment to create patterns and how do the patterns influence ecological function?...(e.g.)...To what extent does spatial pattern affect the ability of systems to recover from disturbance? . . . To what extent is spatial pattern critical to the sustainability of plant and animal communities? (O'Neill et al. 1992)[12]

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[11]For general methodological discussions, see Jørgensen 1983 a, b, c.

[12]For an example of a spatially complicated wetland model where, nonetheless, the intercell movement depends on water flows and not independent organism action, see Costanza and Maxwell (1991) and Kadlec (1986).

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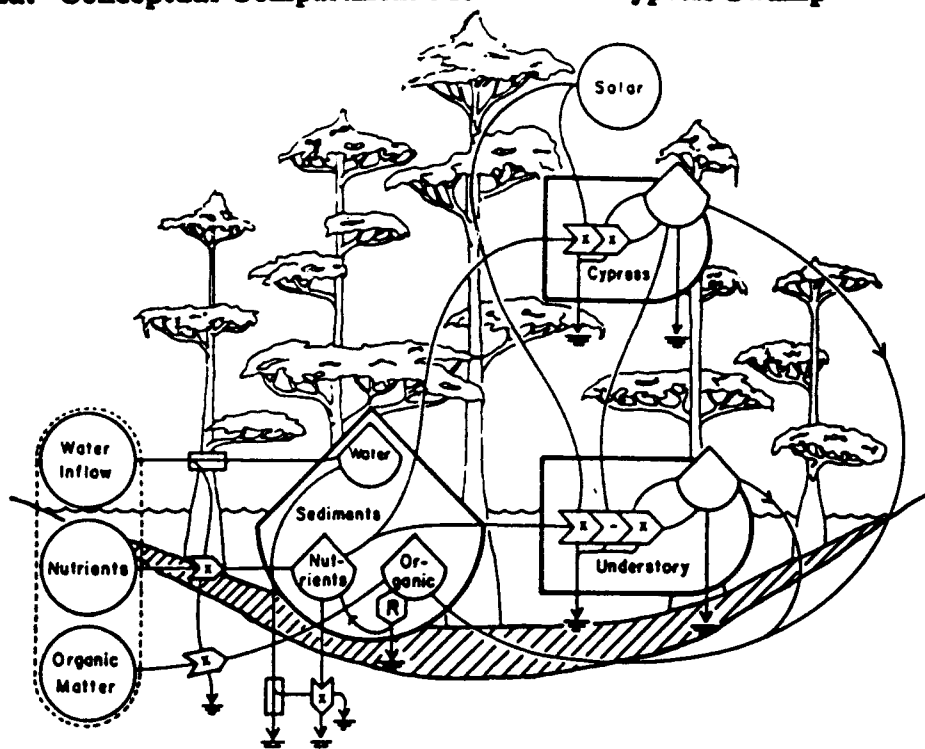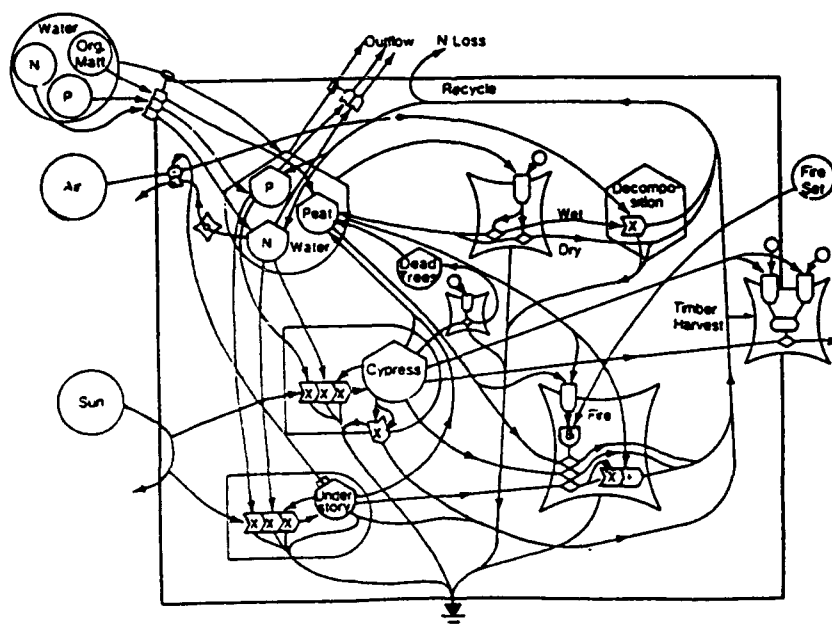**Figure II.2a. Conceptual Compartment Model for a Cypress Swamp**

Figure II.2b. Cypress Dome Simulation Model Schematic

Source: Jørgensen 1983.

TABLE II.2

DIFFERENTIAL EQUATIONS FOR CYPRESS DOME SIMULATION MODEL
(Shown in Figure II.2b. Definitions in Table II.3.)

Cypress

$$\dot{Q}_1 = k_3 Q_1 Q_3 Q_4 J_r - k_5 Q_1^2 - k_7 Q_1 - k_8 Q_1 \left[\frac{Q_2 Q_7}{Q_6} \right] - k_9 Q_1 - k_{56} Q_1$$

Understory

$$\dot{Q}_2 = k_4 Q_2 Q_3 Q_4 J_r - k_{10} Q_2 - k_{11} Q_2 - k_{13} Q_2$$

Nitrogen

$$\dot{Q}_3 = J_5 - k_{29} Q_3 Q_6 - k_{30} k_3 Q_1 Q_3 Q_4 J_r - k_{34} k_4 Q_2 Q_3 Q_4 J_r + k_{31} k_5 Q_1^2 +$$

$$k_{35} k_{10} Q_2 + k_{39} k_{15} Q_7 J_7 + k_{40} k_{16} Q_7 - k_{32} Q_2 Q_3 + k_{36} k_8 Q_1 \left[\frac{Q_2 Q_7}{Q_6} \right]$$

$$+ k_{37} k_{13} Q_2 + k_{38} k_{17} Q_7$$

Phosphorus

$$\dot{Q}_4 = J_4 - k_{21} Q_4 Q_6 - k_{22} k_3 Q_1 Q_3 Q_4 J_r - k_{24} k_4 Q_2 Q_3 Q_4 J_r + k_{23} k_5 Q_1^2 +$$

$$k_{25} k_{10} Q_2 + k_{41} k_{15} Q_7 J_7 + k_{42} k_{16} Q_7 + k_{26} k_8 Q_1 \left[\frac{Q_2 Q_7}{Q_6} \right]$$

$$+ k_{27} k_{13} Q_2 + k_{28} k_{17} Q_7$$

Water

$$\dot{Q}_6 = J_3 - k_{18} Q_6 - k_{19} Q_6$$

Organic Peat

$$\dot{Q}_7 = J_6 + k_7 Q_1 + k_7 Q_1 + k_{11} Q_2 - k_{15} Q_7 J_7 - k_{16} Q_7 - k_{17} Q_7 + k_{57} Q_8$$

Dead Cypress

$$\dot{Q}_8 = k_{56} Q_1 - k_{57} Q_8$$

Sunlight

$$J_0 = J_r + k_1 Q_1 Q_3 Q_4 J_r + k_2 Q_2 Q_3 Q_4 J_r \quad \text{(nonstratified)}$$

$$J_0 = J_{r2} + k_1 Q_1 Q_3 Q_4 J_{r1} + k_2 Q_2 Q_3 Q_4 J_{r2} \quad \text{(stratified)}$$

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TABLE II.3

STORAGES AND PATHWAY DEFINITIONS FOR CYPRESS DOME MODEL
(In Figure II.2b and Table II.2)

Parameter	Description	Initial or Average Value
Q_1	Cypress Biomass	68,000 kcal/m^2
Q_2	Understory Biomass	400 kcal/m^2
Q_3	Nitrogen Storage	4160 g/m^2
Q_4	Phosphorus Storage	340 g/m^2
Q_6	Water Storage	0.32 m^3/m^2
Q_7	Organic Peat Storage	78,000 kcal/m^2
Q_8	Dead Cypress	0.0
$k_3 Q_1 Q_3 Q_4 J_r$	Cypress Gross Primary Production	3277 kcal/m^2 yr
$k_5 Q_1^2$	Cypress Respiration	1721 kcal/m^2 yr
$k_7 Q_1$	Cypress Litterfall	1214 kcal/m^2 yr
$k_8 Q_1 Q_2 Q_7 / Q_6$	Cypress Biomass Lost to Fire	1/k = 10 days
$k_9 Q_1$	Cypress Harvest	$t_{1/2}$ = 4 days
k_{56}	Cypress Kill by Fire	----
$k_4 Q_2 Q_3 Q_4 J_r$	Understory Gross Primary Production	2591 kcal/m^2 yr
$k_{10} Q_2$	Understory Respiration	1295 kcal/m^2 yr
$k_{11} Q_2$	Understory to Organic Storage	1295 kcal/m^2 yr
$k_{13} Q_2$	Understory Biomass Lost to Fire	1/k = 1 day
J_6	Organic Inflow	0-1700 kcal/m^2 yr
$k_{57} Q_8$	Dead Cypress to Organic Storage	1/k = 20 yrs
$k_{15} Q_7 J_7$	Underwater Site Decomposition	2464 kcal/m^2 yr
$k_{16} Q_7$	Dry Site Decomposition	536 kcal/m^2 yr
$k_{17} Q_7$	Organic Storage Lost to Fire	1/k = 1 day
J_3	Water Inflow	7.9 m/yr
$k_{18} Q_6$	Water Outflow	6.4 m/yr
$k_{19} Q_6$	Evapotranspiration	1.5 m/yr
J_7	Dissolved Oxygen	1.1 g/m^2
J_4	Phosphorus Inflow	1.26 g-P/m^2 yr
$k_{21} Q_4 Q_6$	Phosphorus Outflow	0.0
$k_{22} k_3 Q_1 Q_3 Q_4 J_r$	Phosphorus Uptake by Cypress	0.36 g-P/m^2 yr
$k_{23} k_5 Q_1^2$	Phosphorus Leaching by Cypress	0.19 g-P/m^2 yr
$k_{26} k_8 Q_1 Q_2 Q_7 / Q_6$	Phosphorus from Cypress Fire	----
$k_{24} k_4 Q_2 Q_3 Q_4 J_r$	Phosphorus Uptake by Understory	0.46 g-P/m^2 yr
$k_{25} k_{10} Q_2$	Phosphorus Leaching by Understory	0.23 g-P/m^2 yr
$k_{27} k_{13} Q_2$	Phosphorus from Understory Fire	----
$k_{41} k_{15} Q_7 J_7$	Phosphorus Recycle—Wet Decomposition	0.34 g-P/m^2 yr
$k_{42} k_{16} Q_7$	Phosphorus Recycle—Dry Decomposition	0.07 g-P/m^2 yr

TABLE II.3 (Continued)

STORAGES AND PATHWAY DEFINITIONS FOR CYPRESS DOME MODEL
(in Figure II.2b and Table II.2)

Parameter	Description	Initial or Average Value
$k_{28}k_{17}Q_7$	Phosphorus from Organic Storage Fire	----
J_5	Nitrogen Inflow	10.3 g-N/m^2 yr
$k_{29}Q_3Q_6$	Nitrogen Outflow	0.0
$k_{30}k_3Q_1Q_3Q_4J_r$	Nitrogen Uptake by Cypress	5.6 g-N/m^2 yr
$k_{31}k_5Q_1^2$	Nitrogen Leaching by Cypress	2.9 g-N/m^2 yr
$k_{36}k_8Q_1Q_2Q_7/Q_6$	Nitrogen from Cypress Fire	----
$k_{34}k_4Q_2Q_3Q_4J_r$	Nitrogen Uptake by Understory	6.9 g-Nm^2 yr
$k_{35}k_{10}Q_2$	Nitrogen Leaching by Understory	3.4 g-N/m^2 yr
$k_{37}k_{13}Q_2$	Nitrogen from Understory Fire	----
$k_{39}k_{15}Q_7J_7$	Nitrogen Recycle—Wet Decomposition	12.3 g-N/m^2 yr
$k_{40}k_{16}Q_7$	Nitrogen Recycle—Dry Decomposition	2.6 g-N/m^2 yr
$k_{38}k_{17}Q_7$	Nitrogen from Organic Storage Fire	----
$k_{32}Q_2Q_3$	Denitrification	8.1 g-N/m^2 yr @Q$_2$ = 4000

Even recognizing the big spatial question mark there seems to be two advantages to this general model type that make it worth exploring in more depth for the Corps' purposes. First, the techniques of model construction and the principles of model structure are reasonably well worked out so new applications do not have to begin with reinvention of the wheel. Second, the models require commitment to specific hypotheses about the design of the system in question and how the parts interact. Third, at least some of the predictions of such models are verifiable. For example, aquatic model predictions of dissolved oxygen, chlorophyll-A and fish biomass concentrations can be checked by sampling procedures.

On the other hand, an obvious and serious disadvantage of this approach is that such models are demanding of their builders, for they require careful specification of functional forms and of fixed parameter values in the functions, and they usually have to be tailored carefully to individual applications. They also require some sophistication for their solution. Usually they are used to develop steady state predictions and to compare these for assumed natural variation or human interventions. Perhaps as important in the context of this paper, even these models do not necessarily allow those who are studying an area to predict functional performance. For example, while carbon fixation and nutrient cycling and sequestration are really the models' stocks in trade, their links to landscape, erosion control, flood absorption, and even wildlife

richness are, at best, problematic.[13] Finally, it is not straightforward to build human interventions into the models, either the destructive or constructive variety. Interventions that operate on a compartment or relation, such as the introduction of organic material to a stream or harvest of a predator species from any system, are one thing. Changing spatial extent in any dimension or introducing a very long-run toxic are quite another.[14]

4. Models Based on Individual Organisms

One of the criticisms of the carbon or energy flow models is that they do not deal with individual organisms:

> Most mathematical models in ecology, from simple equations of population growth to complex descriptions of ecosystem function, are based on assumptions that violate two of the basic tenets of biology. First, models often combine many individual organisms and assume that they can be described by a single variable, such as population size. This procedure violates the biological principle that each individual is different, with behavior and psychology that result from a unique combination of genetic and environmental influences. Second, most models do not distinguish among organisms' locations. Each individual is assumed to have an equal effect on every other individual. This assumption violates the biological principle that interactions are inherently local.
> (Huston et al. 1988, p. 682.)

The writers of those sentences go on to discuss current work and early results achieved in the field of individual-based models. The examples they cite involve trees and plants (Pacala and Silander 1985; Aikman and Watkinson 1980; Weiner 1986); birds (Thompson et al. 1974; Craig et al. 1979); and fish (De Angelis et al. 1979; Adams and De Angelis 1987). At the community level, they cite work on forests (Huston and Smith 1987; Shugart et al. 1981). At the ecosystem level, they point to work by Aber et al. (1982), Pastor and Post (1986), and Shugart and West (1977).

In their discussion, Huston et al. (1988) make it clear that the major value of individual-based models is likely to be in the strengthening of ecological theory—either through the generation of predictions and hypotheses or through the suggestion of explanations for puzzling phenomena. It is possible, however, to imagine a more practical use for such models if they live up to the promise ascribed to them by Huston et al. (1988). It is not that a new individual-based model would be constructed for every decision problem. Rather, it is that a single generic ecosystem model would be solved many, many times for variations in initial conditions, shocks,

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[13]For example, early aquatic models predicted an undifferentiated fish biomass. The fish compartment filled a niche in the model system but did not respond to changes in system inputs the ways species of interest to humans do (e.g., Spofford et al. 1976).

[14]See Jørgensen 1983d for a discussion of modeling toxic substances' effects in aquatic systems.

spatial changes, etc., and the resulting data would be input to a statistical exercise designed to characterize the model's response surface in several dimensions as a function of background conditions, potential shocks, and possible management interventions[15] (see Section IV).

D. DEFINING RESTORATION AND MITIGATION IN A PROJECT CONTEXT

While we face very substantial difficulties in defining ecological outputs, we need to be clear about the baseline from which the outputs of restoration and mitigation projects are to be measured. While this may seem at first glance fairly trivial—simply a matter of applying the old with or without project stipulations—there are, in fact, some difficulties lurking beneath the surface. To gain a preliminary sense of them, consider the following hypothetical case: An existing project has damaged a wetland area so that the current situation is worse than the pre-project situation. This might be determined by calculating effective habitat area or by some ecosystem function model. That is not important for the example. All that matters is that we can recognize and measure better and worse. Another wetland area, similar in quality to that degraded by the project, lies contiguous to the project boundary. Does purchase of that wetland constitute restoration?

It would seem that generally the answer to that question has to be no. Mere change in ownership has no effect on the natural world. Even if purchase can be said to protect from future development, all that is accomplished is to prevent an even worse future situation; the original project-created degradation has not been corrected. Consider the following simplified accounting for a project that does some damage to natural systems and is expected to lead to indirect damage via development on adjacent lands (Figure II.3).

So purchase and protection can only mitigate the original loss due directly to the project to the extent this strategy is used to prevent degradation by development of lands that would have been developed under without-project conditions. This holds true for other forms of land-use controls, such as purchase of development rights or of special easements. It is not an artifact of fee-simple ownership. The result follows from taking society's view of the project and, in particular, of the regional ecological system.

In general, to restore the situation of the project and its neighborhood, active steps must be taken to change the situation on project lands or on extra land purchased for the purpose of active restoration, not merely to prevent project-inspired development. The same argument holds for mitigation planning at the time of original project construction. Adopting this stance creates some additional challenges and research opportunities:

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[15]This use of carefully crafted micro models to provide input to an effort to characterize the macro response surface, was pioneered by Griffin, Smith, Kopp, and Vaughan (e.g., Smith and Vaughan 1980). It is being used currently by researchers interested in nonpoint source pollution from farm applications of pesticides (Shogren 1992) and is sometimes called "meta-modeling."

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Figure II.3. Existing Project: What is Restoration?

	Without Original Project (Net of Usual Project Costs)	Direct Project-Created Loss	Project-Inspired Development Loss	Development Losses Not Due to Project
Annual Benefits/ Losses	B	L_D	L_I	L_N

(1) With original project: without restoration

   Net Social Benefit $= B - L_D - L_I - L_N$

   Loss attributable to project: $L_D + L_I$

(2) With original project: purchase (and protection) of lands facing project-inspired development

   Net Social Benefit $= B - L_D - L_N$

   Loss attributable to project: L_D

(3) With original project: purchase (and protection) of all lands in vicinity facing development

   Net Social Benefit $= B - L_D$

   Loss attributable to project: $L_D - L_N$

- It is necessary to have a believable technique for forecasting project-inspired changes in land use, including changes in agricultural and forestry practices, in recreation demand, and in flood plain use where flood control is a project output. These use changes in turn imply ecosystem function changes. It is worth noting that the developments we are discussing here are exactly the sort counted as sources of project benefits—e.g., increasing cropping intensity or development of a regional recreation destination resort adjacent to a Corps project. Effectively, an interest in protecting natural systems introduces a new cost term into all such benefit projection exercises.[16]

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[16]It is not enough to be able to predict gross regional changes in economic activity. These must he located in project and non-project space and understood in the context of the overall regulatory situation, including rules that will prevent some otherwise projected uses from occurring at all or will restrict their locations.

- It is generally necessary to understand and be able to employ active restoration techniques. Such techniques are quite highly developed in situations where game species of wildlife are at stake.[17]

E. DECISIONS, DECENTRALIZATION, AND THE ROLE OF ANALYSIS

The world in which the Corps operates has changed quite substantially over the past 15 years. The pork barrel, if not completely gone, is much smaller. With its shrinkage has come a reduction in the utility of a management system designed to encourage local autonomy. Tight national budgets for items outside the dominant entitlement programs have put pressure on all agencies spending discretionary dollars. The pressure takes the form of requirements for justification and for making choices among projects that might, in the past, all have passed review and been proposed, authorized, and funded. In addition, national legislation and regulation limiting agencies' freedom of maneuver, such as the Endangered Species Act and National Wetlands Policy, often require a national overview in application. These trends increase the importance of the center relative to the local units of such agencies, the Corps is not excepted.

On the other hand, restoration projects, like construction projects of all kinds, require nonfederal, usually local, cost-sharing sponsors. While making such projects harder to fund, this requirement also increases the importance of local input into decision processes about restoration. Those who will pay part of the bill want to have some say in the what, where, when, and how much questions, the answers to which define the final project.

These countervailing political forces seem to have almost exactly opposite implications for structuring decision processes and supporting information provision activities where restoration is concerned. To be able to respond to requirements for choices and their justification, the leadership of the agency needs information that allows a centralized comparison among projects. Thus, for example, if an accepted measure of ecological effectiveness existed, the center could use information on project costs and units of effectiveness purchased by those costs in finding an optimal division of any given total restoration and mitigation budget.[18] If ecological outputs have been translated into money terms—benefits—the center would try to maximize the net benefits purchased with its limited budget. In the absence of either of these output measures, the center's problem is exactly like the one currently faced and obscured in

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[17]For trout habitat restoration, see Hunter (1991). Methods for restoring a variety of wetland functions in a variety of settings have also been tried, evaluated, and cataloged. See, for example, Kusler and Kentual (1990). Restoring forest types as defined by dominant tree species) has also been studied and modeled, though validating experiments here necessarily involve very long time horizons. For an example of a restoration modeling exercise, see Phipps and Applegate (1983). For several other examples, see Berger (1990). Dune regeneration—Hiebert (1990) and Pickart (1990), and coal mine site restoration^C4,34 Covert (1990) and Baker et al. (1991) are other examples of techniques with some background literature.

[18]It would try to approximate the result that the best budget allocation would be that at which the marginal cost per unit of effectiveness were equal across all projects.

studies such as that for the Kissimee project: there is no objective rule for picking the best set of projects from those submitted up the chain of command. [It is true that constraints, or output weights, such as those implied by the North American Waterfowl Management Plan (U.S. Fish and Wildlife Service 1986) may help to generate defensible solutions to the budgeting problem.] On the other hand, to be able to deal with local sponsors, the agency probably needs a system that encourages and informs negotiation across several dimensions, including the character and extent of restoration and the nature of any side payments, such as increases in recreation access. This suggests a tiered process in which local units both respond to and generate information. Both that information and the results of local negotiation become inputs to increasingly formal analytical systems as a possible restoration project, or set of alternatives, is considered at successively higher levels.

In these circumstances, the best strategy for the intermediate run seems to be to aim at a range of efforts—improving the output models, providing a prototype for local decision processes, systematizing the way national priorities are used as weights or constraints in the ranking of locally generated projects, and beginning the process of introducing the notion of willingness to pay into the information set passed to the highest levels of the Corps. In effect, constructed will be a highly informal version of a multi-attribute utility function approach to the evaluation of restoration or mitigation alternatives.

In the longer run, there are several competing routes and all probably deserve at least preliminary investigation. Here is a list of candidates:

1. **A more rigorous and formal multi-attribute utility approach.** This is the way DOE has been moving to prioritize waste site clean up efforts. Their model is, however, notably weak on the environmental side and is not really a useful prototype for the Corps' effort (USDOE 1991).

2. The analytical hierarchy approach that has been chosen by DOD for its waste site prioritization (National Research Council 1992).

3. An effort to develop a single effectiveness measure based on complex natural systems models. This seems to be a route unlikely to be successful, but it probably should not be ruled out at this point. The idea would be to improve the current method on the ecological side, sticking with cost effectiveness as a criterion but aiming for a better conceptual basis and one that allows comparison across proposed projects.

4. The evolution of a formal benefit-cost methodology, probably built on techniques for attaching willingness-to-pay numbers to alternative states of the natural environment via some version of the contingent valuation method. This method could not be successful if a *de novo* willingness-to-pay study were going to be required for each restoration proposal.

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III. THE SHORT RUN

In the short run, FY93 and FY94, time will not allow development of new tools or decision processes for dealing with restoration issues. As actual decisions and ranking are required, they will be informed by standard habitat models or, in special cases, perhaps by WET or the bottomland hardwood forest community model mentioned. There may, however, be opportunities during this period to compare and evaluate the available tools in particular case study settings. Seizing such opportunities will be an important, if rather opportunistic, part of short run activities. Another enterprise to be pursued in this period might be called foundation building—searching for and codifying what is known in certain areas of research and what is required of Corps decision makers by federal restoration-related laws and regulations.

Specific suggestions for program elements follow in subsections keyed to the notions of opportunistic case studies and foundation building.

A. CASE STUDY OPPORTUNITIES

Short run case study opportunities include:

1. A particularly useful type of exercise would be the comparative application of several output models to the same problem area—including HEP, PAMHEP, and HES with more than one species—species with quite different habitat requirements if at all possible if resources permitted. The point of the exercise would be, first, to compare the rankings of proposed restoration alternatives generated by each of the species/model pairs. This would give a preliminary idea of the importance of competition and resulting sensitivity of rankings to analytical choices. A second goal would be to document the costs of applying each model for each species. Cost here should be taken broadly to include required commitment of expertise and time as well as out-of-pocket cost. Use of multiple species would generate a version of economies of scale because certain costs, such as travel of documentation teams, would be in effect fixed as the second of a pair of target species was added.

    The basic comparison of the habitat models could be extended as appropriate to include applications of wetland function (WET) and water quality models, again with the purpose exploring the effect on ranking of changing the basis of comparison.

2. Another line of inquiry also could be opened up if the case-study setting permitted. That would be a preliminary exploration of public perceptions of and tastes in both natural systems and decision processes. Because such an inquiry would be quite exploratory, it probably would make sense to proceed via focus

groups rather than formal surveys. If such groups could be convened at several locations across the U.S. but presented with a common agenda, it might be possible to explore, for example, regional differences in the relative importance attached to competing ecological system functions in different settings.

B. FOUNDATION BUILDING

There are several possibilities for the gathering, cataloging, and interpretation of information bases that should be available before intermediate-run work gets underway:

1. In 1975, Resources for the Future published a book that included papers describing several different aquatic ecological models designed to be used in a resource management setting (Russell 1975). The volume followed a workshop that brought together the developers of the various models for discussions about methods, results and challenges. Such an exercise and publication aimed at the broader field of ecological restoration modeling could be useful, particularly under certain conditions:

    • The groups were kept small.

    • Economists and decision scientists were included.

    • The structure was such that no one could get away with a mere sales pitch.

    • Frontier efforts were represented (for example, someone working on modeling at the organism level).

    • The focus on the management context was ferociously maintained.

    Models to be discussed would include those focusing on species and community habitat, on energy flows, and on species populations. Because one big long run problem appears to be the lack of models that cross the aquatic/terrestrial boundary, it would be useful to have both broad types included in the same event.

2. Surveys that would generate a base of knowledge for longer run work and that feasibly could be done in the short run include the following:

    a. An assessment of the state-of-the-art of ecosystem restoration engineering and the cataloging of cost estimates for techniques that seem to work.[19]

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[19]An example of the cost of alternative wetlands creation techniques is found in Shabman and Batie's 1987 work.

This assessment could be tied to the inventory of problem types described and recommended below in point b.[20]

b. An effort to identify the most important mitigation and restoration target systems likely to be facing the Corps over the next decade would help to put a limit on what is otherwise an essentially unlimited problem set. This might be done by using simultaneous research at headquarters and the convening of regional workshops.

c. An inventory of what have been referred to as national overrides or national-level priorities, that set limits on what can be done by way of restoration. These could include for the foreseeable future the requirements of the Endangered Species Act, the current version of a national wetland policy (U.S. General Accounting Office 1991), and the North American Waterfowl Management Plan (U.S. Department of Interior 1991). In the future, there may be policies, based on legislation or executive orders, related to such questions as the introduction of locally nonnative species or the management of freshwater recreational fisheries.

3. In the longer run, a very important question for restoration priority setting is how well individuals—the lay public, legislators, or decision makers—can deal with multidimensional problems. This is because, as already discussed, the output of ecological restoration is intrinsically multidimensional, even though the habitat models most frequently used in current evaluations suppress this. Preliminary investigation of what is known in this regard would set the stage for later work—or conceivably be so discouraging as to make such work low priority. This investigation would extend what has been learned in preparation of the white paper, concentrating on the economics, psychology and decision sciences literatures. (For further discussion of some current evidence, see the material in the next major section on processing vector section.)

4. A final foundation building effort usefully could be put into assessing the state-of-the-art in locally oriented decision processes. These might include Delphi groups, conflict resolution and mediation or arbitration. What would be important here

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[20]An interesting link between restoration work and biological research is suggested by the following quote: (Jordan et al. 1987, pp. 5, 6, and 15). "Usually it is assumed that restoration is a practical matter, a form of applied ecology, and it is taken for granted that it is the insights of more 'basic' research that will provide the basis for successful restoration practice. Ecologists, in other words, are expected to do most of the talking, restorationists most of the listening. In the discussion carried on in this book, we are making a deliberate attempt to turn this around. For one thing, we have systematically ignored the traditional distinction between theory and practice. But more than that we have attempted to unite the two traditions by drawing attention to the tremendous value of restoration, not only as a form of environmental technology, but also as a technique for basic research...Far from being of peripheral interest to ecology, restoration actually deserves to be regarded as an organizing principle for ecological research, the basis for deciding which questions are most worth answering, and which ones are irrelevant or of marginal interest. In other words, it suggests that restoration might provide the basis for organizing, evaluating, and even criticizing, ecological research."

would be to see where and how such techniques have worked to produce stable decisions and what information inputs have been found to be helpful in the applications. Care must be taken in this general area because so much of the literature reads like promotional material for one or another type of nonstandard process for solving intensely political problems. (See, for example, Amy 1987; Bingham 1986; and Susskind and Cruikshank 1987.)

IV. THE INTERMEDIATE RUN

Over the intermediate run—for the two or three fiscal years following FY94, let us say—two broad sorts of accomplishments might be expected from a program aimed at improving the Corps' ability to set and justify priorities for ecological restoration projects. First, more ambitious case studies—in some cases amounting to experiments with analytical methods and decision process—could be under taken. Second, a more adventurous rese~ ~h program could be attempted. The focuses of all activities should be primarily on three questions:

- What are the best practically available ways of predicting the outputs of restoration projects?

- How can those outputs best be communicated to participants in the decision process, be they representatives of local interests or staff to the assistant secretary of the Army (Civil Works)?

- Can a structure be devised that allows local interests to work out their conflicts and reach agreement on a preferred restoration strategy, and that also produces and transmits information up the chain of command to help the Corps headquarters choose among locally preferred alternatives at the national level and to justify those choices to a skeptical OMB and Congress?

A. CASE STUDY OPPORTUNITIES

It seems most unlikely that there will be either enough decision problems or enough internal resources to do a large enough set of experiments to conclusively answer questions about what works. It should still be useful, however, to begin an exploration of the interconnections among analysis and decision process in this context. What this might mean in practice is roughly this: Four or five real restoration decision problems could be approached with a common protocol specifying the local decision process and the type of information to be passed up the chain. The output modeling and prediction mechanisms for each case study might be different, if only because no common methods for aquatic and terrestrial systems yet seem to be operational. A major dimension of difference among the cases would be in the type of information given to and asked of the local actors. For example, in one or two cases, information on rankings of systems or valuation of functions might be provided based on experiments or on literature review. In others, only material describing the vector of outputs from the proposed restoration project might be provided. Analogously, some local groups could be required to produce both an agreed on project and a ranking of competing alternatives. Other groups could be required to try at least to produce willingness to pay (WTP) (i.e., benefit values for all projects seriously considered).

The first objective of the case studies would be to assess the ability of local groups to reach agreements and to transmit justification to regional and national levels. The second would be to explore what works by way of input and output from these exercises.

B. FURTHER RESEARCH

1. Ecological Outputs

It is possible to imagine that significant improvements might be possible in the ability of ecologists to predict the outputs, in several functional dimensions, of restoration projects. It is almost certainly inappropriate for an economist to speculate how this could be accomplished—on what models it might require—but some comments on technique more generally might not be amiss. First, no single ecological model or even model type seems able to deal with even the half dozen functions that have been used as illustrations in this paper. Second, currently, ecological models that have been used in resource management settings have been tailored to local circumstance both in the compartments chosen and in specific parameter values. Such a highly location-specific approach, with models that are already complicated and not necessarily fully satisfactory anyway, suggests that it may be worth the Corps' time, effort, and money to create a single all-purpose, multifunction productive model, probably as a linked series of underlying models. Once it existed, such a model could be solved many times for varying parameter values and the results used to estimate a complicated response surface in the system-function space. This response surface could then be treated analogously to the tables and formula that underlie the habitat and community models (see footnote 15).

2. Vectors, Values, and Decisions

It has been argued that the essence of problems involving human interventions in the environment is that they involve as output changes in the elements of vectors. Those vector elements often are referred to as the functions of ecosystems. On the other hand, the essence of cost-effectiveness analysis, or indeed of any technique that allows for straightforward, systematic and routine choices among alternative elements in the agency budget-building process, is that those with responsibility be able to compare two scalars, or two single numbers. It also has been acknowledged that building a bridge between these two elements is a tricky problem, with philosophical and political as well as technical and practical dimensions to it.

There appear to be three major contenders for the title of preferred basis for constructing a scalar out of the multifunction output of any successful predictive model:

- The use of scientific units
- The use of a "multi-attribute utility function"
- The use of willingness-to-pay dollar values

a. Scientific Units

It is the position of an apparently substantial though unknown fraction of ecologists and other environmental scientists that outputs of ecological systems, thus the change in output due to restoration or mitigation, can and should be expressed in scientific units or at least in units that are implicit in the ecological system and its equilibrium, as prices are implicit in an economic equilibrium.

The term scientific units usually seems to mean embodied carbon, potential energy, or solar energy capture.[21] The appeal of such methods appears to lie in the measurement techniques involved, which are scientific in the sense that the values obtained do not depend on complicated and sometimes questionable assumptions about human behavior or decision processes. These values do not, however, purport ultimately to be independent of human preferences. In 1989, Costanza et al. stated the following:

> The method looks at the total amount of energy captured by natural ecosystems as an estimate of their potential to do work for the economy. It yields an estimate of a comprehensive (in that it should include all possible useful outputs) upper bound on the economic value of the products of natural systems. It is an upper bound because not all of the work done by the system is necessarily useful to the economy.
> (Costanza et al. 1989, p. 350)

Without embroiling this white paper in what seems an intense but ultimately somewhat esoteric debate, it can be pointed out that there is a distinct mismatch between the calls for a functional view of ecosystems and for a scientific output measure. To understand this concept consider only the landscape function. There is no evidence for—and a great deal of casual evidence against—the notion that the landscape function of an ecosystem is correlated even roughly with its gross primary productivity. Some landscapes seem, in fact, to be valued because of their bleakness—their low productivity. If this observation is correct, and if similar observations can be made about the relation between an embodied or captured energy measure and other ecosystem functions agreed to be important, then the two approaches will generally produce different rankings for the same set of described ecosystems.

The notion that certain prices are implicit in ecological equilibria is set out rather ponderously and by analogy with economic systems in Amir (1989). Without seeing some application of these notions to a functioning system in two or more steady states, it is impossible to make a confident judgment of its utility. It is speculated in this white paper, however, that this notion holds no substantial promise for application by the Corps

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[21]For an example of the use of the last of these, along with a conversion to dollar terms and comparison with valuation based on services to human society, see Costanza et al. (1989). For a more fundamental discussion see Costanza (1980).

of Engineers. Finally, for an interesting discussion of creating a scalar measure of the diversity of an ecological system, see Weitzman (1992).

b. Multi-Attribute Utility Techniques

The USDOE system being developed for setting priorities among contaminated-site cleanup operations was mentioned above (USDOE 1991). In application it looks rather like the community habitat model (O'Neil et al. 1991) in that a great deal of normalization goes on in order to wash out the problems created by disparate scales and units among the different functions, and in that the final scalar result reflects a weighting scheme applied to the normalized underlying utility values. The major and truly significant difference between the two approaches is that these final weights in the USDOE model are derived from interviews with decision makers. Further, the USDOE system was designed to work in tandem with a local public participation process, while itself being aimed at the national budget justification problem.

Much effort has and will continue to go into refinement and review of the USDOE system: Its promise in the Corps' problem context is sufficient such that it seems reasonable to suggest an intermediate-run effort to adapt this strain of decision science to the restoration prioritization problem. The reason it seems wise to wait on this until the intermediate run is that some technique for making multidimensional (multifunctional) predictions of the results of proposed actions must be in place before there will be multiple attributes to worry about.[22]

c. Willingness to Pay

There is a train of thought that says roughly, "So we produce output vectors. We can just present the alternative output vectors to the relevant audience and let them produce rankings." If this approach works, it does not produce a scalar effectiveness measure, but it does allow interested parties to order the alternative projects both in terms of costs and of output vectors. A choice might then be made on any number of more or less arbitrary grounds, including minimizing the sum of the ranks, where the number one output alternative gives the highest ranking output vector and the number one cost alternative gives the least cost.

Logically, a problem precedes this last arbitrary step. Individuals have, in principle, the same difficulty ranking ecological output vectors as society has ranking states of the society's world. That is, if the individual must try to make do with only orderings of the elements of the vectors and if all possible vectors are eligible for judging, there will be no rule the individual can use that will always produce a clear winner. In particular, the person may well find it impossible

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[22]The Department of Defense has developed a priority model for its own hazardous waste sites (NRC, 1992). This model uses the "analytic hierarchy" process to create a scalar measure of environmental and human health risks. No effort is made to include multiple environmental dimensions and no weights are obtained from decision makers or the public. But there are nonetheless weights implicit in the model, and the NRC report criticizes these as arbitrary and unjustified.

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to decide among the members of some subgroup of vectors within which her preferences cycle.[23] The only way this result can be avoided for all possible vector comparisons is for the individual to have a cardinal ranking function that assigns a scalar value to each vector, to which these could still be ties but not cycles. Therefore, if it is believed that individuals can rank all possible ecosystem function vectors for any system, we must also believe that they have some sort of function that provides a scalar summary number for each vector.

It is not really a huge conceptual step, then, despite the protestations of scholars such as Sagoff (1988) and Rolston (1986), to thinking about a scalar-producing ranking function for vectors of ecological function outputs. One more step carries us to the possibility of asking people to scale that function to their incomes, regarding it as their willingness to pay.[24]

Perhaps this is no big conceptual jump, but certainly it is a jump over a number of practical hurdles. In particular, even though the so-called contingent valuation method (CVM) literature has increased greatly in the last decade, experiments or applications in which people have been asked to value complicated vectors of different attribute elements is still much less common than work with one-dimensional problems. Thus, for example, people have been asked about visibility improvements (see the citations in Cropper and Oates 1992); about water quality improvements (Mitchell and Carson 1989); about specific recreational opportunities (Bishop and Heberlein 1979); about avoiding diseases and accidents (Magat et al. 1988); and about drinking water safety (Kwak 1992). But in all these cases and many other similar ones, whatever each respondent may have thought about, the alternatives were couched as scalars. For example,

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[23]Here is a simple example developed by analogy. A standard version of Arrow's paradox (one of the symptoms of his impossibility theorem) involves three voters and three states of the world, among which the voters are to choose. If the preference pattern is:

Person	Preference ordering of states of the world
I	A > B > C
II	B > C > A
III	C > A > B

by majority rule, in sequential, pairwise voting, with no permanent elimination, the society exhibits the following cyclic preferences:

$$A > B > C > A > ...$$

Consider next a single person who must decide among three vectors, each consisting of three elements. $\{A\} = (Q_1^A, Q_2^A, Q_3^A)$; $\{B\} = (Q_1^B, Q_2^B, Q_3^B)$; $\{C\} = (Q_1^C, Q_2^C, Q_3^C)$. Further, let's say that each Q_i is measured in its natural units and that more is preferred to less in each case by our individual. Let's further say that the elements rank in their own terms as follows:

$$Q_1^A > Q_1^B > Q_1^C$$
$$Q_2^C > Q_2^A > Q_2^B$$
$$Q_3^B > Q_3^C > Q_3^A$$

Now if, for example, our individual tries to decide by an internal "majority vote"—that is, she says she prefers A to B if she prefers a majority of the elements of A to their counterparts in B, then, the following pattern of preferences over the vectors would be produced: $\{A\} > \{B\} > \{C\} > \{A\}, ...$

[24]This discussion ignores the already rich literature on the relationship between rights and the appropriate way to ask such questions of people, and on the distinction between willingness to pay and willingness to accept compensation. See, for example, Knetsch, 1990, and Gregory, 1986.

Mitchell and Carson's experiment used different levels of water quality defined by the kind of recreation supportable at each level of dissolved oxygen, suspended sediment, and temperature. They also asked for the willingness to pay to see that all water bodies in the U.S. were at least at each alternative level. Bishop and Heberlein asked about a day of a very specific recreational experience. Kwak defined the threat in terms of being protected against a widely publicized chemical spill and its aftermath in another part of Korea.[25]

In addition, psychologists, at least those identified in the process of preparing this white paper, appear quite pessimistic about the ability of human cognitive processes to deal with multidimensional inputs to judgmental processes (see, for example, Ebbesen and Konecni 1980). This pessimism seems to be based on experimental work involving such tasks as judging the degree of similarity between two faces or bodies based on pictures and on written descriptions of the salient features.[26] Specific research directions for improving the contingent valuation method on the basis of insights from the psychology literature are proposed by Harris et al. (1989).

There is some encouraging evidence in other literature of people's ability to deal with questions involving vectors. An example that does not involve dollar values but rather indexes of desirability for natural places or features described in vector terms is found in Angermeier et al. (1991). Examples of the valuation of vectors include Loomis (1989); Bergstrom et al. (1990); and Jones and Stokes Associates (1990), in which three-dimensional program packages with each dimension having three alternative effort levels were compared for managing the fish and wildlife resources of the San Joaquin Valley.

What is being suggested here is that individuals be invited to think about attaching WTP scalars to alternative vectors of ecosystem functions. Is it possible to describe these functions in ways that convey ecological reality but also speak to the individuals?[27] Second, how many functions can be included before subjects become confused? If this could be done for one, two, or three vectors for a single type of system, would that exhaust the patience and attention span of respondents?

It is only fair to point out what already may have occurred to the reader—it is at least conceivable that values of each ecosystem function could be developed more or less independently and without the use of the contingent valuation method. Recreation is the function

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[25]There are other dimensions involved in these studies besides those potentially implicit in the natural world conditions described. An important set is that of the reasons for the values stated—especially the contrast between use and nonuse, the controversial nonuse values arising from whatever motivation (See, for example, Walsh et al. 1984; Stevens et al. 1991; Silberman et al. 1992; Kahnemann and Knetsch 1992; Di Bona 1992; and Bishop and Welsh 1992).

[26]For a slightly more upbeat assessment of human capability, see Phelps and Shanteau (1978).

[27]We are finessing the question of to whom we pose these questions: Corps decision makers? Members of Congress? Members of the general public?

with the most advanced methods in this regard.[28] Farber (1987) estimates the value of wetlands in their role as protectors of settlements against hurricane wind damage. The type A natural resource damage assessment techniques referred to apply to wildlife population effects, which are then valued as prey for recreational or commercial harvests or as prey for watchers (Grigalunas et al. 1988).

Two major difficulties arise when this route is travelled, however. First, finding function-by-function values that are exhaustive and mutually exclusive is at least extremely difficult, perhaps impossible. Second, any function that leaves no footprint in any human market, however indirect, could not be valued in this way.

A structured way to investigate the potential for the use of CVM in the ecological restoration context would be to compare in a single setting the operation of several methods of attaching scalars to the outputs of alternative restoration projects. To make the enterprise believable it should involve sites that are or could be candidates for restoration. They also should involve system types for which habitat-based models are available and for which gross primary productivity could be easily estimated. Finally, there should be sites for which multiple ecological system functions will be affected by restoration. The bottomland, hardwood forests of West Tennessee, where stream channelization has been common, might contain a good candidate. For these many situations, the outputs of each alternative should be measured by each of the alternative methods—at least a habitat suitability model (preferably one as broadly based as that of O'Neil et al. 1991); a gross primary production/energy flow model; and a contingent valuation application. The latter would require some sort of multifunction predictive model, but this might be ad hoc and informal as long as the information provided to respondents was consistent with that produced by the models underlying the other two approaches. That is, at a minimum, the WTP questions could involve the values of predicted changes in habitat and gross primary productivity. Perhaps landscape and flood-control outputs could be characterized as well for the right setting.[29]

The output of such studies could be interpreted in different ways by different parties and, in any case, could never tell us which effectiveness measure is correct or politically most acceptable. However, the studies would be most useful if some ranking inconsistencies were found among the methods and if the underlying reasons for them could be examined.[30]

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[28]For an effort to value the recreation opportunities of the National Forests, see McCollum et al. (1990). This effort produced regional per-recreation-day values that could be used in a decentralized way.

[29]There would be no particular point in asking CV questions based on the already scaled "habitat units." Though we might find out how much such a unit was worth at the margin and on average for a particular system type, we could not explore the potentially more interesting question of how people feel about the underlying characteristics of the plot in question, especially those that would be affected by the restoration alternatives in question. Clearly, however, we could not ask respondents to compare 45 element vectors, so care would have to be used in creating questions that convey the essence of the habitat changes predicted but stop short of doing the index-number arithmetic. For an example of a CV study that looks only at landscape and then only at the visual effects of pollution damage, see Crocker (1985).

[30]On thinking about ongoing experiments of this sort as contests, the outcomes of which help us refine both current theory and future experiments, see Plott (1991).

V. THE LONG RUN

Long-run prediction would be a perilous game were there ever anyone keeping track to hold the predictor to account for inevitable failures. This is only slightly less true for an effort to set out a long-run research program, where what it later seems useful to investigate will depend on what has turned out to look promising in some shorter run and on the evolution of institutions and problem setting that relate to the methods at issue. However, we suspect that, in the long run, the Corps will find it useful to have a willingness-to-pay-based system for restoration project budgeting purposes. Routine application of the WTP transformation to multidimensional outputs of predictive ecological models, however, cannot practically depend on site- and problem-specific CVM studies. Rather, at some point, it will be necessary to do a very ambitious meta-valuation project in which a substantial national sample of individuals will be asked a series of questions that will allow the generation of a valuation response surface related to ranges of values in the functional dimensions discussed so often above. This might be facilitated by the use of interactive computer software along the general lines developed and used by Viscusi and Magat (Magat et al. 1988), to ask about tradeoffs among potential illnesses and accidents. The settings for the hypothetical changes probably should be varied to help provide at least a preliminary idea about any system-specific biases. (e.g., Do people relate to streams more readily than to swamps?)

The surveys also will have to be designed to come to grips with such issues as the extent of the appropriate market for different scales of ecological intervention. That is, where does WTP fall effectively to zero for the representative person (Sutherland and Walsh 1985; Smith 1992). It seems clear that the absolute answer will depend on the system being examined. This project also probably should involve rather simple questions about a variety of systems subject to change and located differently with respect to the sample of respondents. The overall goal of the exercise would be to produce a tool, that did not require fresh study for every new restoration project, for application at the field level .

VI. SUMMARY AND CONCLUSION

Contained in this discussion, albeit in a somewhat discursive way, is a research program extending over five or more years and designed ultimately to provide the Corps with a conceptually defensible but entirely practical system for making budget decisions about ecological restoration projects. The elements of the program are summarized in Table VI.1 for ease of reference and comparison.

The potential importance of the questions raised by the Corps' desire to do a better job of restoration decision making goes far beyond that of defining the problem, however, a substantial part of the ongoing debate about environmental policy—spotted owls, isolated superfund sites, even global warming—turns on how we think about and value alternative states of ecological systems and their components. While the Corps almost certainly has neither the inclination nor the budget to attempt to provide definitive answers to these questions, it can hardly avoid making an important contribution to the general debate.

Beyond that opportunity lies the more practical chance to put ecologically and economically sound methods in use at the field level. Such an outcome would be the 1990s version of earlier work that made narrower cost-benefit analysis and natural hazards analysis part of the work-a-day decision-making world.

TABLE VI.1

ELEMENTS OF A RESEARCH PROGRAM FOR THE RESTORATION PROJECT BUDGETING PROBLEM

Short Run	Intermediate Run	Long Run
Research		
• Assessment of state-of-the-art in ecological system modeling appropriate to restoration.	• Construction of a set of multifunctional ecological models keyed to Corps' needs. Multiple solution and response surface generation.	• Large-scale survey research attempt to find WTPs for alternative restoration outcomes in many settings and places. Effort to produce a "response surface" using meta modeling techniques.
• Survey of restoration engineering capabilities.	• Investigation of a multi-attribute utility model possibility in Corps' restoration setting. Construction of an experimental prototype.	
• Attempt to identify the coming generation of restoration problems.		
• Inventory of national-level constraints on local restoration actions.	• Extension of comparative application of habitat models to include an effort to obtain willingness to pay (WTP) from a survey sample for alternative restoration outcomes.	
• Assessment of economics, decision science, and psychological literatures on human ability to deal with vectors.		
• Assessment of state-of-the-art alternatives (to standard institutions) for local restoration decision making.		
Experiment		
• Comparative application of alternative habitat and rival output models.	• Experimental assessment of information use and output from local restoration decision processes.	
• Focus groups exploring public perceptions of and tastes for natural systems and for local decision processes.		

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APPENDIX A

Some Observations Based on the Bottomland,
Hardwood Forest Community Habitat Model

The bottomland, hardwood forest community habitat model of O'Neil, et al. (1991) involves the observation of 45 dimensions of habitat (and thus a restoration application would involve the prediction of the post-restoration values of each of those dimensions). Those dimensions are first aggregated via tables and formulae into eight "plot variables" (PV) and 5 five "tract variables" (TV). The makeup of the tables and the shapes of the functions are suggested by the literature but not formally derived either from theory or empirical work. Those 13 variables are in turn aggregated respectively into a "plot suitability index" (PSI) and a "tract suitability index" (TSI) which are then themselves multiplied to produce an overall "habitat suitability index" (HSI). At the plot level aggregation the formula used is roughly an averaging one. Something close to a geometric average is taken of each of three subgroups of the PVs and then the arithmetic average of these subgroup averages is taken. Because the PVs all lie between 0 and 1, this formula guarantees that PSI will also. The method used to get TSI from the TVs is more complex and justified by the literature but involves several arbitrary scalings to again guarantee that $0 < HSI \leq 1$.

Nonetheless, at the end, 45 dimensions of a complex habitat have been combined into a scalar. And by projecting areas and the scalar HSI, the effectiveness of any restoration action can be expressed in "habitat units" (HU). One approach, then, to the effectiveness problem when more ecological functions are projected would simply be to become yet more aggressive and develop ways to normalize and combine the pre and post project function values using common sense but ultimately arbitrary formulae.

To tie this notion down just a little, consider the function of CO_2 fixation. A functional index might be based on the relative importance of fast as opposed to slow growing species, corrected for the importance of perennial plants as opposed to annuals, and perhaps corrected again for the importance of perenials that produce material that can be harvested and used in, say, construction or the production of materials such that the fixed carbon would not be re-released to the atmosphere as CO_2 at least for many years. Let

F =   fraction of tract plants that grow more quickly than some chosen standard
P =   fraction of tract plants that are perennial
U =   fraction of tract biomass that is judged likely to end up in "permanent" products
        rather than as firewood or simply slash waste.

Then we could define the CO_2 fixation index, C as: $C = F \cdot P \cdot U$ and $0 \leq C \leq 1$[1]

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[1] One of the minor problems index creators have is that by using the multiplicative forms that make it easiest to guarantee that the function value can be kept below 1.0, they create the zero problem: If any one of the constituent arguments is zero, the product is also.

To begin to see some of the problems created by this overall approach, even in the hands of quite skillful operators, consider the O'Neil et al. 1991 work in more detail. The formulae these researchers chose for Plot SI (PSI), Tract SI (TSI), and overall Habitat Suitability Index (HSI), are as follows:

$$HSI = PSI \cdot TSI$$

$$PSI = \frac{(PV_1 PV_2 PV_3)^{1/2} + (PV_4 PV_6 PV_7)^{1/2} + (PV_5 PV_6)^{1/2}}{3}$$

$$TSI = \frac{15.18}{100.4} (TV_1 TV_2 MA)^{0.236} TV_4 TV_5$$

where:

TV_1 = % of total area more than 100m from the tract boundary.

TV_2 = a factor equaling the product of a measure of the "permeability" of the tracts bordering areas and of a measure of the availability of other bottomland hardwood forests within 2 km of the tract boundary.

MA = measured tract area.

TV_4 = a factor that is lower the more important agricultural and urban/industrial land uses are upstream of the bottomland forest in question.

TV_5 = a factor that is lower the more severe and prolonged the human-caused disturbances to which the forest is subject.

PV_1 = a factor reflecting the average diameters of the trees in the sample plots from the tract.

PV_2 = a factor reflecting the extent of overstory cover on the sample plots.

PV_3 = a factor reflecting the availability and types of "mast" found on the sample plots. (Mast is roughly nuts).

PV_4 = a factor reflecting the elements of an old growth forest found in the sample plots.

PV_5 = a factor reflecting the moisture regime found in the sample plots.

PV_6 = a factor reflecting the extent of understory cover found on the sample plots.

PV_7 = a factor reflecting types and extent of ground layer features found on the sample plots.

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PV_8 = a factor reflecting the extent of interdispersion of different moisture regimes in and near the sample plots.

A first observation is that PV_1 through PV_8 and TV_4 and TV_5 are all scaled between 0 and 1 using either formulae or tables entered with the field observations (eg, number of old growth elements). Not all the formula are monotonic in the 0, 1 interval, reflecting the possibility that too much or too little of some elements may be possible. None of these formulae or tables results from an empirical fitting of data. But some of the relations used are obviously more ad hoc than others. (For example, the disturbance term (TV_5) is 0.95 if the tract is subject to a one-time, short-term disturbance and 0.75 if it is subject to disturbances severe enough to lead to a cessation of reproductive activities. One might ask, why 0.75 and not 0.15 or 0.45 or 0.05?) Even the most obviously ad hoc might be judged the best available by a panel of experts, but another sort of question is whether there is data available or being gathered that would allow the functions and tables to be checked and improved in a reproducible way.

The forms of the PSI and TSI equations have some interesting implications in themselves, independently of the underlying calculations that produce the PV_i and TV_i indices. A few examples follow:

1. In the definition of PSI, the use of square roots on the triple product terms (instead of the cube roots that would produce geometric averages) implies that doubling every PV_i would produce a value of PSI that was more than twice as high as the original. More precisely,

$$PSI' = \left[\frac{2^{3/2} + 2^{3/2} + 2}{3}\right] PSI = 2.55 \text{ PSI}$$

2. The elasticity of PSI with respect to any underlying index, PV_i, is given by the ratio:

$$1/2 \left[\frac{(PV_iPV_jPV_k)^{1/2}}{(PV_1PV_2PV_3)^{1/2}+(PV_4PV_6PV_7)^{1/2}+(PV_5PV_8)^{1/2}} \right]$$

where i, j, k equals 1, 2, 3 or 4, 6, 7 or 5, 8 with $PV_k = 1$.

One implication of this result is that the influence of a change on any PV_i on the overall PSI, and hence of HSI, is greater, the greater the values of the PV_j and PV_k with which it is associated in the formula.

3. Everything else equal, if the sum $PV_i + PV_j + PV_k$ is held constant, the contribution to PSI of the product is greater the smaller the differences among the elements.

4. The elasticities of TVI, and hence HSI with respect to TV_4 and TV_5 are both 1.0, necessarily larger than the elasticities with respect to any other of the underlying variables; and, as a practical matter for balanced situations, probably much greater. Yet these indices reflect the most clearly ad hoc of the relations used to translate observations into numbers on the 0,1 interval.

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